INVESTIGATION OF PARTICLE MOTION IN A SWIRLING FLUIDIZED BED USING PARTICLE TRACKING VELOCIMETRY

by

MOHD NUZUL SYAZWAN BIN MOHD RAHIM

Bachelor of Engineering (Hons)

(Mechanical Engineering)

SEPT 2013

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Investigation of Particle Motion in a Swirling Fluidized Bed using Particle Tracking Velocimetry.

By

Mohd Nuzul Syazwan bin Mohd Rahim

A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

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(AP Ir. Dr. Shaharin Anwar Sulaiman)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2012

CERTIFICATION OF ORIGINALITY

This is to certify that all the work submitted in this project are of my own work unless specified in the references and acknowledgements, and that the original work contained within have not been undertaken or done by unspecified sources or persons.

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(MOHD NUZUL SYAZWAN BIN MOHD RAHIM)

ABSTRACT

Fluidized bed is a technology which allows a bed of solid particles to be fluidized. It has a wide array of industrial application such as combustion or gasification of biomass, metal coating and solid drying. In order to further enhance the technology, a new type of fluidized bed called swirling fluidized bed (SFB) was introduced for which it has overcome the drawbacks existed in conventional fluidized bed such as low particle usage range, slow fluidization process and particle elutriation. SFB however is relatively a new type of invention and not fully utilise in industrial world. One of the reasons is due to the lack of research been done on it. One of the aspects concerned is the particle motion inside SFB of which no clear research has been done upon. Hence, this project will study the effect of particle motion inside the SFB when subjected to three different variables; namely blade angle, blade inclination angle and particle density. Particle motion in this case refers to the velocity of the particle movement when subjected to different condition. In this experiment, those varying conditions are blade angle (9°, 12°, 15°, 18°), blade inclination angle (10°,15°) and three sets of particles with different densities. The particle velocity is determined by particle tracking velocimetry (PTV) method, a method which analyse two successive images to determine particle trajectory. From the data collected at the end of the experiment, 6% velocity reduction occurred for every 3° blade angle increment and 9% velocity reduction for every 5° blade inclination increment. Finally it was found out that by increasing the particle density by 10%, the resultant particle velocity is reduced by 20% when subjected to the same initial air jet velocity. The result obtained from this experiment can give a better understanding of the particle dynamics when subjected to fluidization process inside SFB. It could serve as a guideline to further improve the SFB design which allowed it to function more efficiently for the use in the industry.

ACKNOWLEDGEMENT

First and foremost, the author would like to express her highest gratitude to the supervisor, AP. Ir. Dr. Shaharin Anwar Sulaiman, for all the motivation, knowledge and advices that has been shared. The help received from him have led the author to a clear path in overcoming numerous obstacles when conducting this project.

The author would like to thank other personnel which contributed in making this project succeful. Some of the personnel mentioned are Mr Vinod Kumar, Mr Ramzy Elneel, Mr Alaldeen Abdullah and Mr Khairul Anwar, of whom have given help be it small or big for the author to complete the project.

Finally, the author would also like to express gratitude to Universiti Teknologi PETRONAS for providing the facilities either for doing the experimental work or researches in undertaking the project. Also personal thanks given to the family and friends whom gave constant support throughout.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

1.1.1 Fluidization

Fluidization is a process whereby a bed or cluster of solid particles is injected with a sufficient upward flow of fluid (liquid or gas) until it achieves a state similar to the liquid itself (McCabe, 1985). This process is almost similar to liquefaction with the only difference is that liquefaction can involved either solid or gas behave into liquid like characteristics after being subjected to the right environment.

When a fluid flow is injected onto the bottom of the solid particle bed, it will move upward through the whole bed via the gap or empty spaces in between the solid particles. At low fluid velocity, the drag force acted on the individual particle is much smaller than the weight of the particle itself. By increasing the velocity of the liquid flow, the drag force is increased up until it reach a critical point where the drag force is equal to the particle weight. This point is called bubbling regime and it is a point where the solid can be said to start to behave as a fluid. The following set of figures showed the summary of the fluidization process.

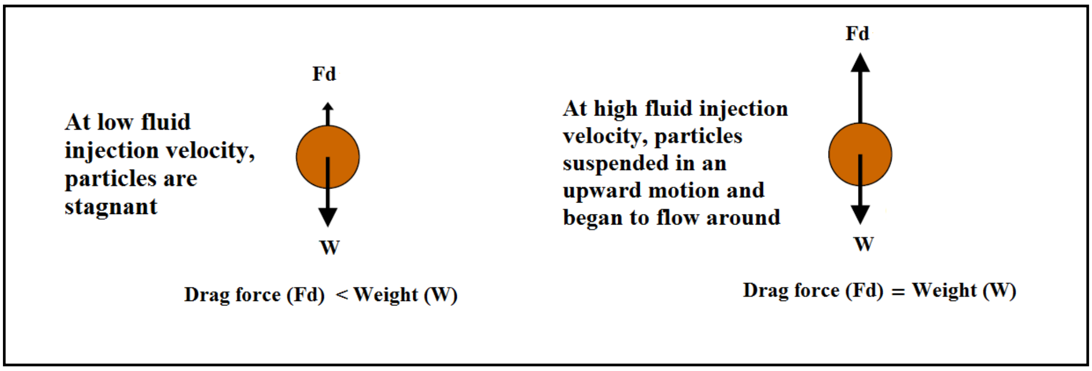


Figure 1.1.1.1 Force balance between drag force and weight of the particle in two different conditions.

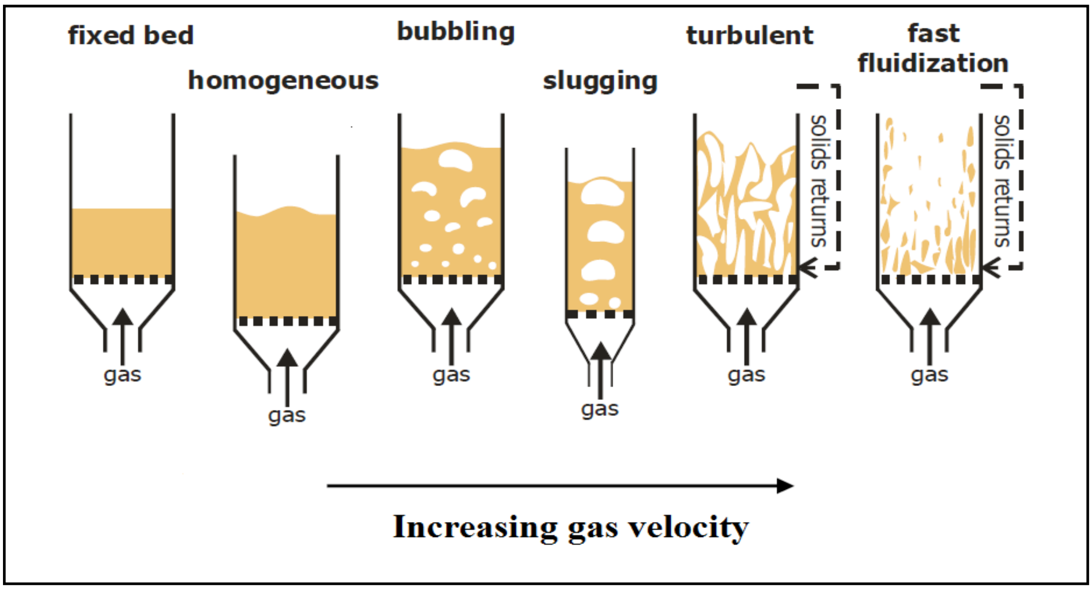


Figure 1.1.1.2 Showing different flow regime that occurred at increasing fluid injection velocity (van Ommen, 2010).

Fluidization as of today is widely used in various industries. Chief among them are combustion or gasification of biomass, metal coating and solid drying. It is without question that any advancement and improvement in the research of this process will contribute greatly towards the world's technological progress.

1.1.2 Swirling Fluidized Bed

Swirling fluidized bed (SFB) is an improved version of a conventional fluidized bed. A conventional bed, as shown in the previous figure is a mechanism that simply allows the solid particles to be suspended with an injection of gas at the bottom of the bed directly. SFB on the other hand applies the concept known as air swirling. It is a configuration of certain components which allows the gas flow from the bottom of the bed to swirl or circulate before it comes into contact with the solid particles.

The components which helped in creating the gas swirling phenomenon are blades and central cone. Both sets of these components are shown in the following figure.

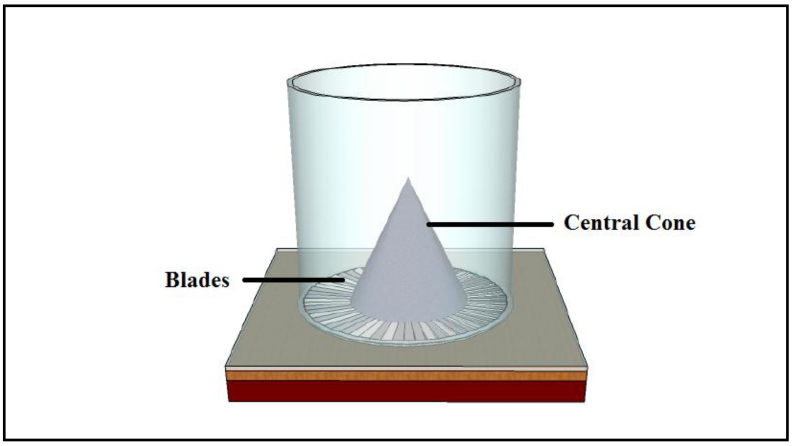


Figure 1.1.2.1 Position of blades and central cone within a SFB.

Collectively, both the blades and central cone are called distributor, name as it is due to its primary function to distribute gas flow injection in a circular motion. The blades are arranged in circles each at a specified inclination angle. This helps the gas that been blown from below to circulate. The central cone on the other hand helps the gas flow in one specific direction, either clockwise or anti clockwise by simply blocking the gas from blowing at the centre of the bed which, if allowed, may cause gas flow disturbance.

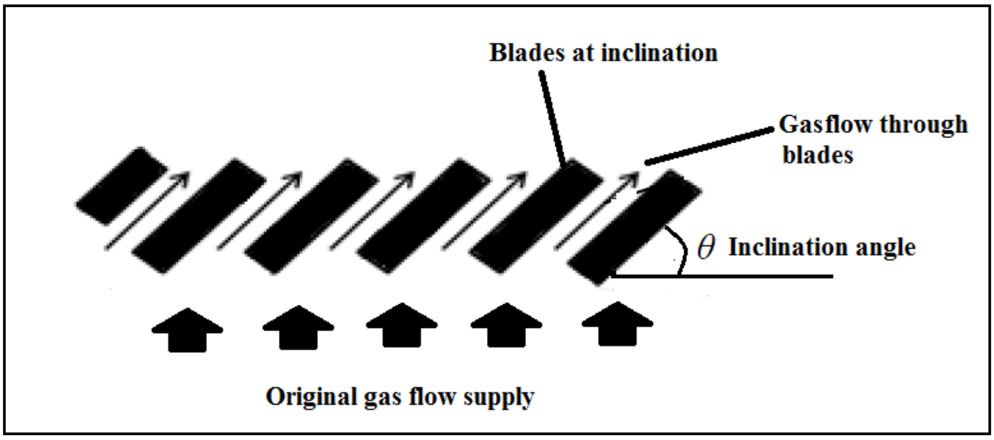


Figure 1.1.2.2 Cross section of the blade arrangement

The gas injection that enters the bed chamber after it flow through the blades is consists of two types of velocity vector namely vertical component (Vsinθ) and horizontal component (Vcosθ). The vertical component produced the fluidization effect of the solid particles while on the other hand; the horizontal component of the velocity is responsible for the swirling motion of the bed particle.

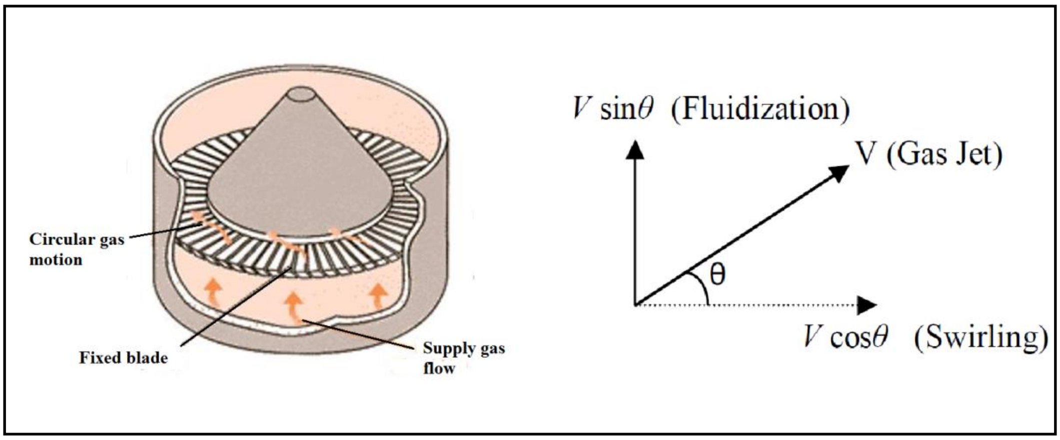


Figure 1.1.2.3 Showing air flow through the distributor (left) and its corresponding vector component (right).

The advantage of SFB in comparison with the conventional bed is that the gas flow is evenly distributed throughout the whole surface area of the bed interior. On top of that, the swirling motion of the solid particles caused by the rotating gas flow allows more intermixing between the particles which makes for more efficient fluidization process.

1.1.3 Particle Tracking Velocimetry

The word velocimetry relates to the study or research of the velocity of a certain body. Particle tracking velocimetry (PTV) is a velocity research method which applies an optical method of measuring the instantaneous velocity of particles through flow visualization (Vukasinovic, 2004). PTV basically implies a spectral analysis of a group of particles images on a set of target sectors known as interrogation area.

For this experiment, a high speed camera is assembled at the top of the SFB setup to take the overview positions of each particle within the interrogation area. A set of image then is taken within a specific time interval between each frame. After that, two frames are taken and superimposed with one another to make comparisons in terms of the particles' positional changes. These comparisons will determine the vector (velocity and direction) of the particles which been tracked.

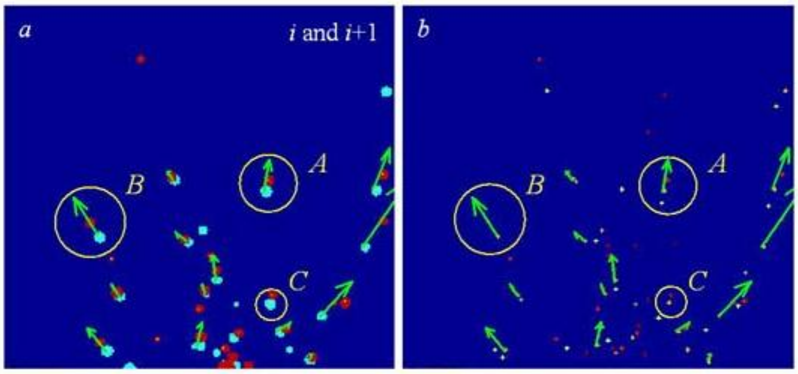


Figure 1.1.3 PTV vector analysis sample

As shown by the previous figure (Figure 1.1.3), the left hand side part shows the superimposed figure of successive image taken at a fixed interrogation area with the blue dot indicates the initial position and the red dot indicates the final position of the same particle after a specific time interval. The right hand side figure shows the clean vector in which the particles is removed leaving only the green arrow which indicates both the velocity; determined from the length of the arrow, and also the direction the particle was moving.

1.2 Problem Statement

As stated earlier, SFB is a technology which has huge potential especially in the industries of energy and manufacturing sector. Despite this, the research and development done on the technology is fairly limited and thus its potential cannot be fully harness. One of the critical aspects of the research that are about to be conducted in this project is the PTV analysis on the particles' velocity that undergo fluidization process in the SFB. This research is crucial in order to maximise the efficiency of the process studying on the particle velocity when subjected to several different design setup, mainly the blades configuration and the density of the particles itself.

1.3 Objective

The objective of this project or research is to investigate the effect of particle density, blade angle and blade inclination onto the velocity of particles inside the SFB. This is done using the PTV method discussed earlier.

1.4 Scope of Study

This project involves using a total of 24 different configurations of experimental parameters, which are four sets of blade angles, two sets of blade inclination angle and three different types of particles with different densities. The first part of this project involved using a high speed camera; all of these 24 configurations are being subjected to imaging process whereby a quarter of the bed is being recorded for a specific duration of time. This will provide a set of images that will be subject to PTV analysis.

The second part of this project involved subjecting the images taken during the first part for PTV analysis. Using MATLAB program, this images will be scrutinized in order to obtain the velocity of the particles for each of the 24 experimental configurations. Once done, the project will enter its final phase which is reproducing the data obtained in the form of tables and graph. These results will be discussed in order to find the factors involved and possible shortcomings and improvement which can be suggested in the future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Fluidization Particle Classification

Fluidization is a process where a bed of solid particle is being injected with fluid flow until the initially solid bed behaves as it is a fluid. One of the important aspects in fluidization is the solid particle being used itself. When conducting a study on fluidization, it is important to use a wide variety of particles species or types. Particle species such as in this case refers to the shape or geometry of the particles. Each species reacts differently when subjected to fluidization process and thus, it is very important to classify these types of particles.

Realising the importance of particle classification, Geldart (1973) proposed a classification method known as “Geldart Grouping”. The method classified particles into four distinct groups, which are named A, B, C and D. Through this method, particles are being sorted out based on their density and mean particle size which are shown in Figure 2.1.

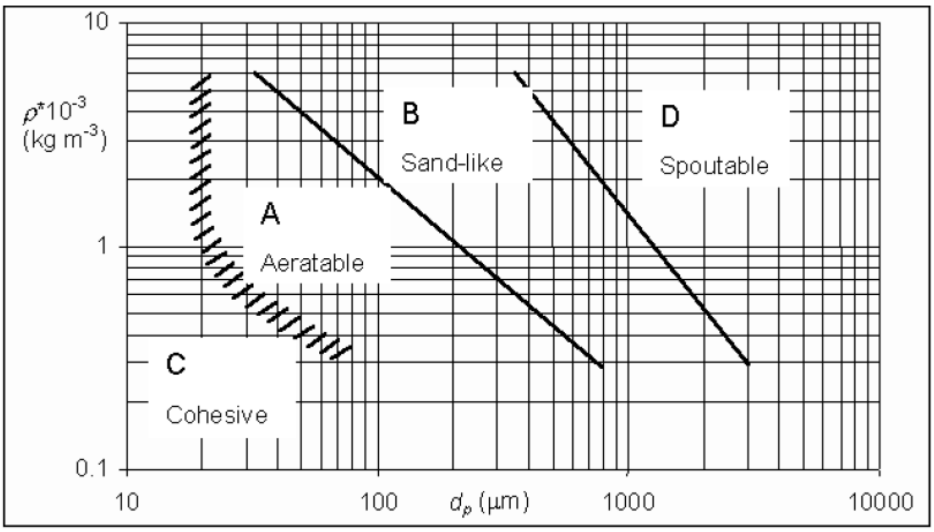


Figure 2.1 Geldart’s classification of particles based on density (y-axis) and mean size (x-axis).

In general, each group exhibit different behaviour when subjected to fluidization process. According to Geldart (1973), group A particle exhibit dense phase expansion after fluidization is achieved whereas group B particle forms bubbling at maximum fluidization velocity. On the other hand, group C particle is almost impossible to achieve fluidization state whilst group D particle is those with high density and size which required the most energy transfer in order to make it achieve fluidization state. Classification of particles is essential as to avoid confusion when conclusion from a research is applied to another which uses different class of particles.

2.2 Swirling Fluidized Bed

Systematic studies of swirling fluidized bed are relatively limited despite increasing usage in today’s industry. Ouyang and Levenspiel (1986) proposed a new improvement on the conventional fluidized bed in which they design a spiral distributor made of overlapping blades arranged in circular shape. This allows the fluid injected to swirl around inside the bed. The invention, now known as swirling fluidized bed (SFB) allow for better efficiency of fluidizing the solid particle based on the quality of the fluidization process itself and also the heat transfer coefficient.

As time goes by, Chyang and Lin (2002) conducted a study on the influence of SFB on the fluidization pattern. Their SFB is a more improved version where included a multi horizontal nozzle distributor. Their design has been determined to increase the quality of fluidization by reducing the elutriation phenomenon when compared to the previous version of SFB. At the same time, another type of SFB is built. Screenivasan and Raghavan (2002) invented a version of SFB with distributor blade arranged at an inclination to allow proper gas flow distribution. In this model, depending on the bed weight, it was found out that the bed pressure drop decreases with increasing air jet velocity.

Up until 2011, study on hydrodynamics of the overall bed is still being studied in which an experiment is being conducted on SFB with annular blade distributor which was done by Batcha and Raghavan (2011). The findings published concluded that the effect of blade geometry is negligible on the bed performance. This is based on the regime of operation which is of similar quality when comparing one blade geometry to another. It is then on the same year, another aspect of the SFB is experimented which is the heat transfer within the bed. This study, done by Mohedeen et al (2011) uses a Geldart type-D particle. In the study, the wall to bed heat transfer coefficient were measured and a decrease in the wall heat transfer coefficient as the bed height is increased.

From all the papers discussed above, it is found out that no concrete study has been made on the aspects of particle motion within the SFB. Most of the studies discussed upon the overall bed behaviour as a whole rather than the individual particle itself which is play an important role in understanding on how the quality of fluidization can be improved. Hence, this experiment will research upon those aspects with hope that it will enhance further understanding on the fluidization process as a whole.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter is divided into three sections (excluding this section). The first section (Section 3.2) is devoted to the experimental parameters that will be investigated. The second section (Section 3.3) discussed on the experimental apparatus setup whilst the last section (Section 3.4) is devoted to explaining the steps taken in performing PTV analysis. Furthermore, Section 3.4 will be further divided into several parts in order to fully elaborate the steps taken when applying the PTV method.

As with any other project, it is important to have a schedule to guide the work that will be undertaken smoothly. Figure 3.1.1 and Figure 3.1.2 showed Gantt chart for Final Year Project (FYP) 1 and FYP 2 respectively. It should be noted that this Gantt chart only serve to provide general guidelines on when each specific activities should be conducted. Depending on several factors such as equipment availability and some unexpected delay, the schedule may subject to some minor alterations.

NO.	WEEK / ACTIVITY	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1.	Preliminary Research Work	■	■													
2.	Literature Review		■	■	■	■	■	■		■	■	■	■	■	■	■
3.	Study of Particle Imaging Velocimetry Technique				■	■	■	■								
4.	Experiment Planning							■		■	■					
5.	Fabrication of Mounting Support											■	■	■		
6.	Image Acquisition														■	■

Figure 3.1.1 FYP 1 project time line and schedule.

NO.	ACTIVITY \ WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.	Image Acquisition	■	■	■	■	■	■	■							
2.	Image Processing							■	■	■					
3.	Data Analysis and Interpretation										■	■	■		
4.	Report Writing								■	■	■	■	■		
5.	Submission of Technical Paper													■	
6.	Oral Presentation														■
7.	Submission of Report														■

Figure 3.1.2 FYP 2 project time line and schedule.

The Gantt chart presented revealed the activity for both the experiment and also papers that needed to be published as per required by the university. For the experimental work that needed to be done, it can be summarized by Figure 3.1.3 which shows the experimental flow chart. This flow chart will be elaborated further in the following sections of this chapter.

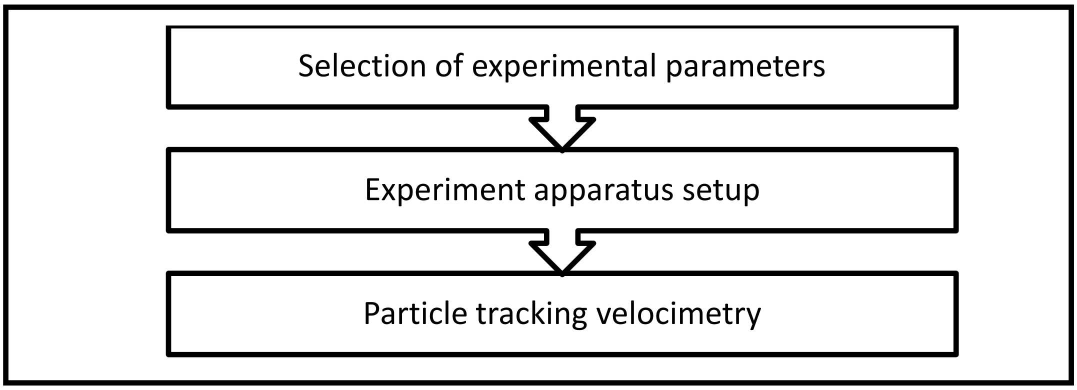


Figure 3.1.3 Flow chart for the experimental activities.

3.2 Selection of Experimental Parameters

Experimental parameters refer to the variables which are in interest to be discussed and research upon. The parameters are chosen based on the objective of the project and the one that are relatively not being studied in detail by previous researches. This ensures that this project will be original and meaningful. For this project, the following parameters are being chosen.

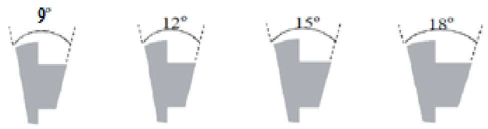
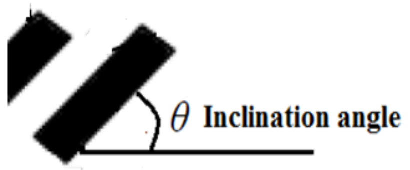
A) Blade fin angle	• 9° • 12° • 15° • 18°	
B) Blade inclination	• 10° • 15°	
C) Particle density	Particle A = 971 mg/cm^3 Particle B = 1246 mg/cm^3 Particle C = 1312 mg/cm^3	} all set with diameter of 6 mm

Table 3.2 Experimental parameters chosen for the project.

Blade angle refers to the angle between one side of the blade fin to another. In general, the smaller the blade angle, the bigger the gap in between the blade arrangement. Blade inclination on the other hand refers to the angle of the blade position relative to the horizontal plane. The bigger the angle, the more upward the trajectory of the air being allowed to flow through. Finally, there is the particle density. For this experiment, three densities are being chosen and for the sake of consistency, all the three sets of particles are fixed with 6mm spherical ball shapes.

With four blade angles, two blade inclinations and three particle densities, it will give a total of 24 sets of combinations. All of these combinations will undergo PTV analysis in which the particle velocities results for each one will be recorded and tabulated.

3.3 Experimental Setup

To conduct the experiment, a lab scale model of a swirling fluidized bed (SFB) is used. The model is mainly constituted of two parts, the first one is the air supply part and the second one is the swirling fluidized bed part. The air supply part supply air into the base of the SFB, whilst the SFB part is where the fluidization of solid particles takes place. The layout of the whole model is shown in Figure 3.3.1.

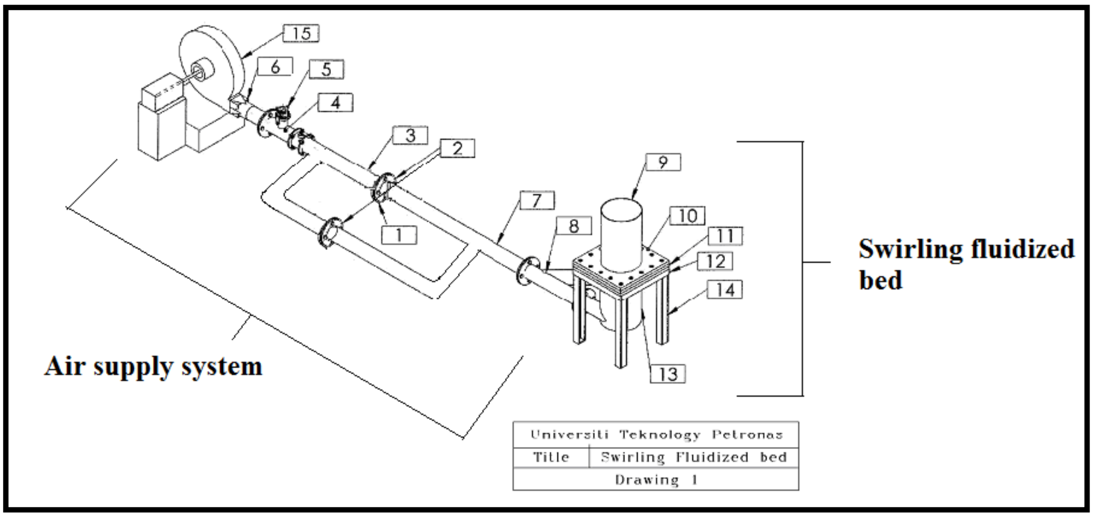


Figure 3.3.1 Schematic diagram of lab scale model of SFB.

No.	Components
1	Orifice meter
2	Flange
3	Pipe
4	Pipe bypass
5	Butterfly valve
6	Connector
7	Pipe
8	Y Pipe

No.	Components
9	Bed column
10	Column flange
11	Distributor flange
12	Support frame
13	Chamber column
14	Column legs
15	Blower

Table 3.3.2 Showing the components name for each label.

For the bed column, its wall is made of Plexiglass 30 cm in diameter. Sixty blades are assembled inside the slot in between two circular blade holders. The outer holder is 30 cm in diameter whilst the inner holder is 20 cm diameter. In the middle of the bed, a circular cone is mounted on top of the inner holder. For more clarity, Figure 3.3.3 showed the top view of the bed while Figure 3.3.4 shows the side schematic diagram of the bed.

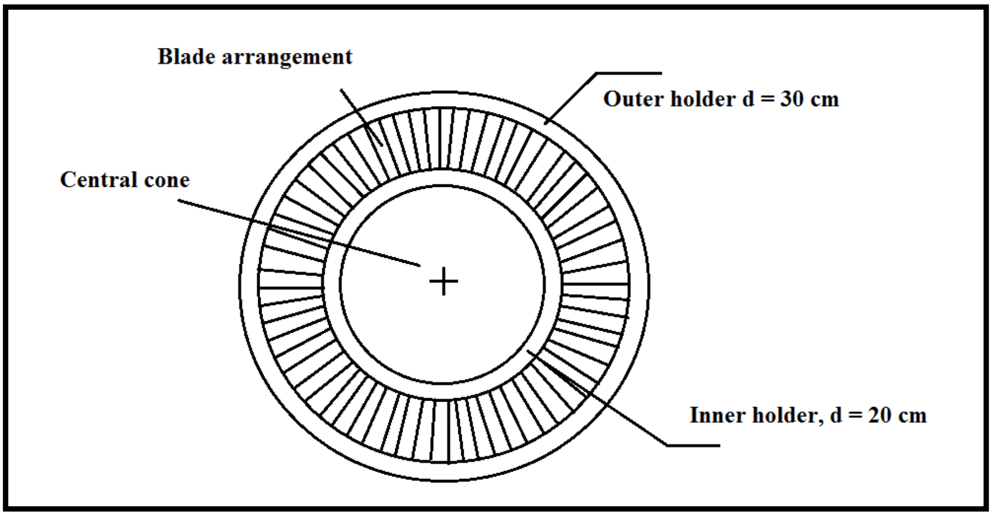


Figure 3.3.3 Showing the top view of the bed column.

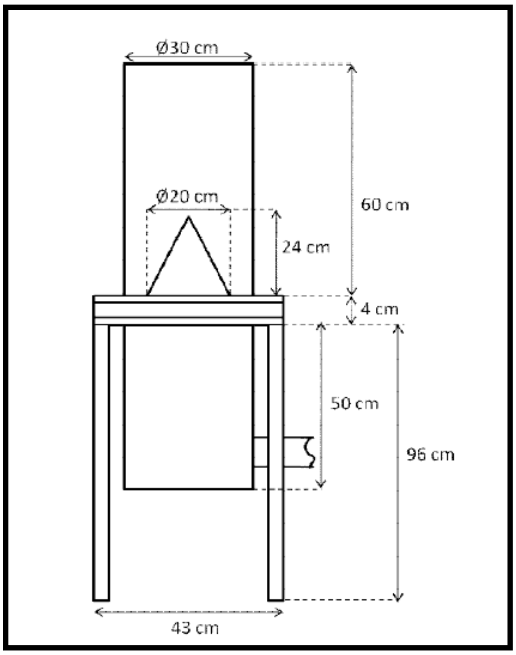


Figure 3.3.4 Dimensions of the SFB from side view.

In order the successfully do the PTV analysis, several special equipments is needed. The first one is the high speed camera. The high speed camera functions to take photograph of high velocity motion which distinguished it from normal camera. This is important as during a high velocity fluidization, the particles could move as much as one metre per second which is out of range for normal camera to follow. For this experiment, the high speed camera in used is the Phantom ir300 model manufactured by Vision Research Incorporated.

Figure 3.3.5 High speed camera Phantom ir300 model used for the experiment.

Maximum Frame Rate	6688fps at full revolution
Maximum Resolution	2048 x 2048
Sensor	Extended-range CMOS sensor
Image Depth	14-bit

Table 3.3.6 Specifications of the high speed camera used.

The high speed camera is mounted directly on top of the SFB using a tripod stand. In addition to that, a light source is added in the form of spotlight. This spotlight functions to highlight the interrogation area or the area of the SFB that will the focus of the experiment. It allowed the high speed camera to capture precise and clear image of the particles within the bed. Figure 3.3.7 illustrates the configuration of the whole equipment setup which includes the SFB and the PTV related equipments together with its related dimensions.

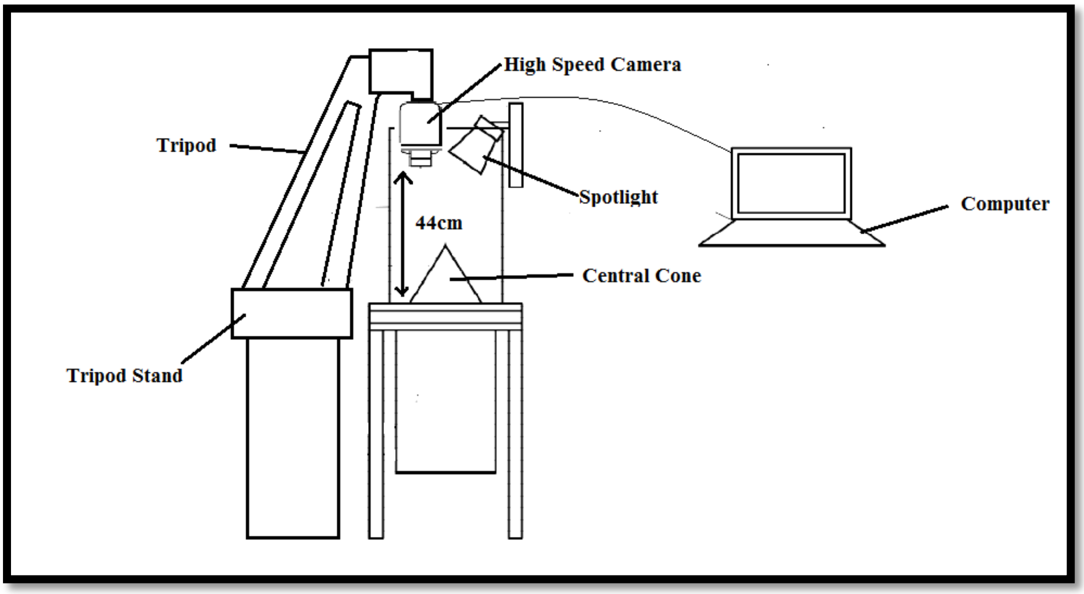


Figure 3.3.7 Apparatus setup for the experiment

3.4 Particle Tracking Velocimetry

Particle tracking velocimetry or PTV involved the use of two successive images captured in which the particles' positional changes between the two are analyzed in order to determine its velocity component. PTV in general is being done through the stages shown by the below schematic figure.

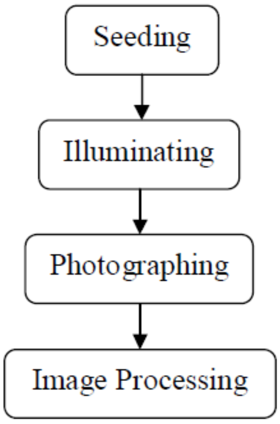


Figure 3.4.1 PTV procedure schematic diagram

3.4.1 Seeding

Seeding involved putting the particles into the bed. These particles will be the subject of imaging and hence it is important for it to be distinguished clearly, especially when considering the fact that the high speed camera can only take images in monochrome (black and white). In order to do this, a special type of particles' colour combination is set up. This combination involved two types of particles colouring, the first one is the background particle makes of dark coloured particle. The other one is tracer particle, a light coloured particle which will be the focus of the PTV. For all three sets of particles, the background particle is set to be 75 percent or 900 gram whilst the tracer particle is set to be 25 percent or 300 gram, giving a uniform bed weight of 1200 gram for each set. Figure 3.4.1.1 showed the sample of the particle colour distribution used in this experiment.

Figure 3.4.1.1 Showing particle colouring distribution for Particle A.

3.4.2 Illuminating

Illumination or lighting is essential in getting the best possible images of the particles being experimented. The function of illumination process is mainly to assist in further distinguishing the contrast of particles' colour. In addition to that, the bed is often a little bit dim due to its height; as such the light source used should provide enough lighting for the experiment to go through. For this task, a spotlight is being used. The spotlight will be used to light up approximately a quarter of the bed chamber which will be called as interrogation area. This interrogation area will be the focal point of the experimental analysis. Figure 3.4.2 shows the use of the spotlight in this experiment.

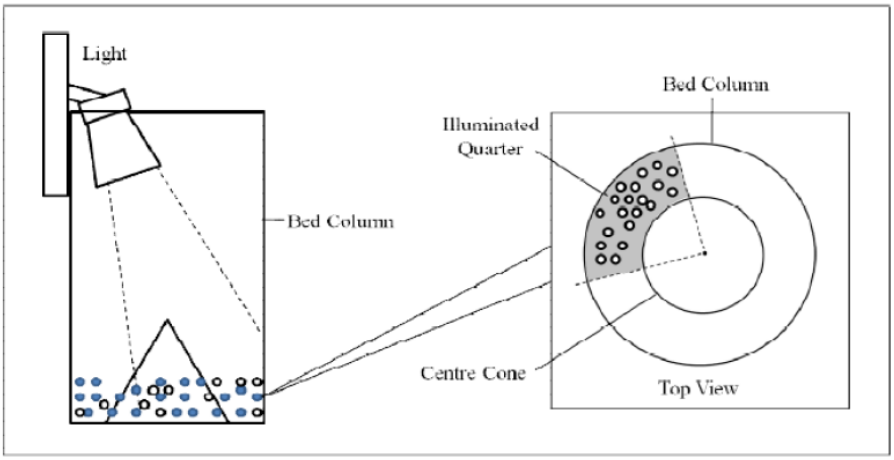


Figure 3.4.2 Showing the illumination system application for the experiment.

3.4.3 Photographing

Photographing or imaging is a process whereby using the high speed camera, each of the 24 parameters' combination is being recorded in terms of the particles' movement. The image being taken is set for the properties shown in Table 3.4.3 which in the authors' understanding, should be the most suitable for analysing process in the later stages.

1) Frame rate	100 frames per second
2) Image resolution	768 pixels x 768 pixels
3) Duration	3 seconds (300 frames)
4) Orifice pressure when image was taken (mm H_2O)	50, 70, 90, 110, 130, 150

Table 3.4.3 Properties of the image taken using the high speed camera.

3.4.4 Image Processing

Image processing is the final and the most important element in the PTV. For this experiment, a analysis method known as Binary Image Cross- Correlation method (BICC) is used. This method implies the use of two successive images with a specific time interval. For each images, the tracer particles is being located and compared with one another in order to determine the path it has taken in between the two images.

The first step in the image processing is to convert the image into binary form. Binary images are basically image with two binary codes numbering, which is 0 and 1. In simple terms, binary image only consists of pure black and white images. This is done in order to make it easier to trace particles as the software used in order to do PTV analysis traces particle based on their contrast. Figure 3.4.4.2 shows the results of the conversion process.

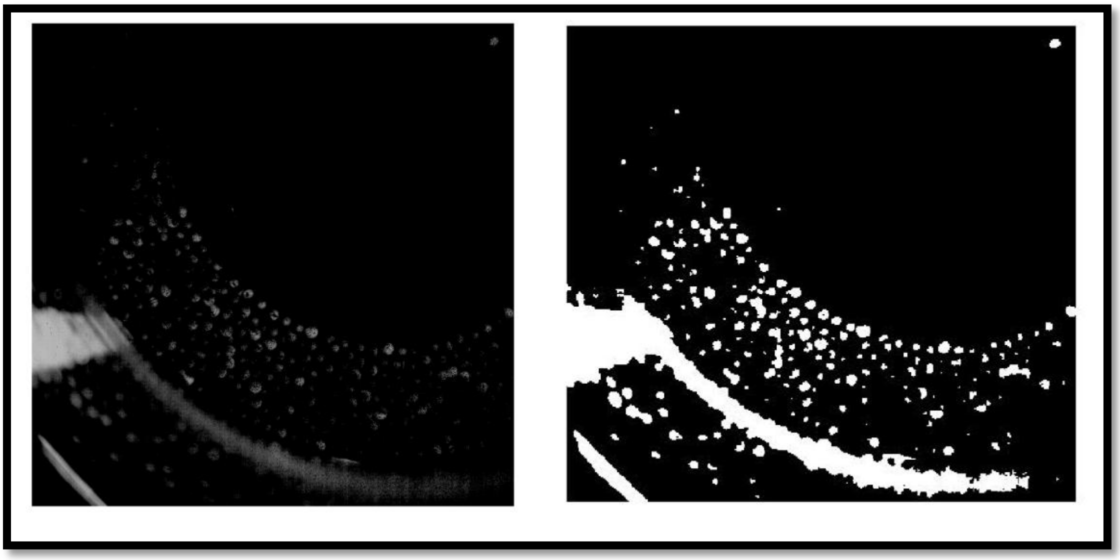


Figure 3.4.4.2 The image on the left is the original image while image on the right is the conversion into binary form.

After the conversion process, the image is then is being masked out of unwanted area. It should be noted that the converted image still maintain some of the so called ‘noisy image’. Noisy image is defined as the images which are the result of lighting reflection. One area of obvious noisy image in the image taken during the experiment is the particle reflection on the plexiglass. Another area removed is the centre of the cone which is not needed in the analysis process. Through masking process, this unwanted area is removed leaving only the particles’ path along the blade assembly.

After the image has been cleared out of any unwanted area, than the analysis process can be done. Using PTV lab extension of the MATLAB software, the image is analysed using the BICC discussed earlier to produce velocity lines which indicates both the direction the particles took and also the velocity for each line, which can be determine by its length. A velocity diagram is then produced by taking a certain segment of the analysed image in which the average velocity of velocity lines within that segment is being calculated. Finally, all of the velocity data is being tabulated and graphed for the final result.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Data Analysis

Data analysis refers to how the final data is obtained and presented. This section is divided into two parts which is determining the superficial velocity and interpreting the image analysis.

4.1.1 Determining Superficial Velocity

Superficial velocity refers to the velocity of air that enters the bed chamber. As explained in Section 1.1.2, the air from external environment is being absorbed into the piping system through blower. The air than enters the plenum chamber before it is channelled into the blade arrangement within the SFB chamber.

The superficial velocity of the air is determined from the pressure drop measured at the orifice plate. As indicated in Table 3.4.3, the orifice pressure reading when the image is taken is at 50, 70, 90, 110, 130, and 150 mm H_2O respectively. Using this numbers, the air superficial velocity can be calculated using both of these equations (Equation 4.1 and Equation 4.2).

$$\dot{Q} = A_0 \, C_d \sqrt{\frac{2(P_1 - P_2)}{\rho(1-\beta^4)}} \qquad (4.1)$$

$$V_{superficial} = \frac{\dot{Q}}{A_{bed}} = \frac{\dot{Q}}{\frac{\pi}{4}({D_o}^2 - {D_i}^2)} \qquad (4.2)$$

$\dot{Q}$ = Air flow rate through the pipe.

A_0 = Pipe cross sectional area.

C_d = Drag coefficient of orifice plate (in this case = 0.668)

$P_1 - P_2$ = Pressure drop at orifice

ρ = Density of air.

β = Pipe diameter ratio.

D_0, D_i = Outside and inside diameter of bed chamber

Example of calculations for orifice pressure drops of 50 mm H_2O:

$$\dot{Q} = \frac{(\pi)(0.062)^2}{4}\ (0.668)\sqrt{\frac{(2)(490.33)}{(1.2)(1-0.5^4)}}$$

Orifice pressure converted into Pa unit

$$\dot{Q} = 0.0595$$

$$V = \frac{0.0595}{\frac{\pi}{4}(0.3^2 - 0.2^2)}$$

V = 1.515 m/s

The same calculations are done for all of the other orifice pressure drop numbers which are then presented in Table 4.1.1.

Orifice pressure drop (mm H_2O)	Superficial Velocity (m/s)
50	1.515
70	1.794
90	2.034
110	2.249
130	2.445
150	2.626

Table 4.1.1 Calculated superficial velocity for each orifice pressure drop reading.

4.1.2 Interpreting Analysed Image.

Using the MATLAB software, the PTV analysis allowed the images taken to be converted into velocity field diagrams. Velocity field diagrams are a set of images which showed the movement of the particles via arrow arrangement. Figure 4.1.2 showed example of velocity field diagram with the following properties; particle C, blade angle 9°, blade inclination angle 10°, orifice pressure 110 mm H_2O.

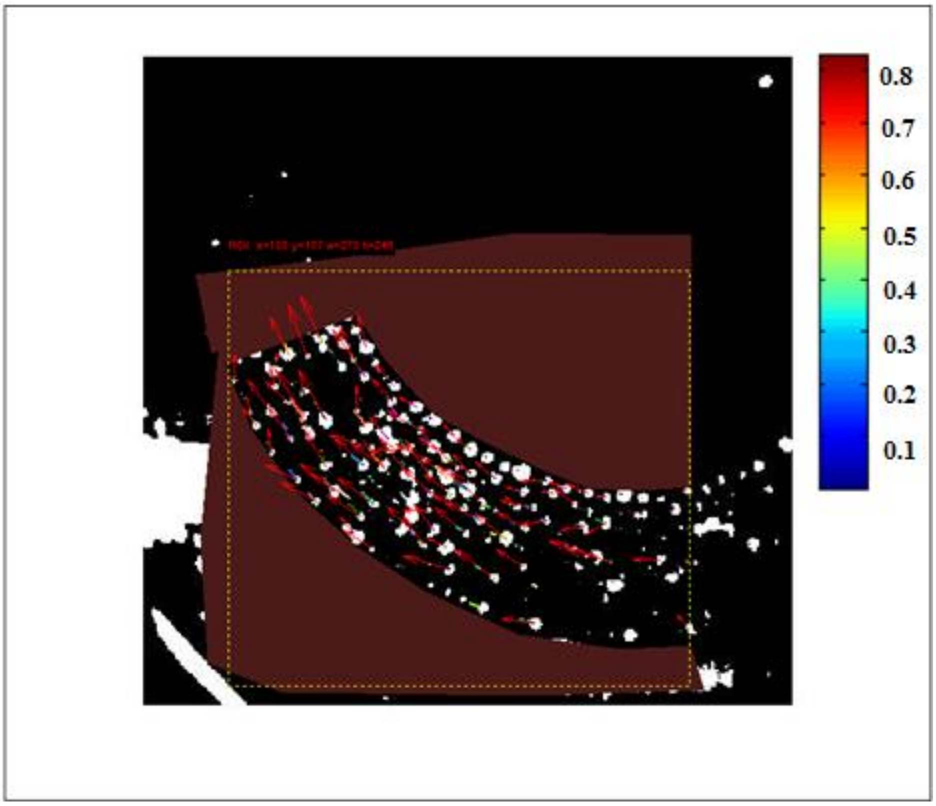


Figure 4.1.2.1 Example of velocity field diagram.

As explained before, velocity field diagram showed the movement of particles via a set of arrows. Noted that these arrows are of different colours which indicate different velocities as shown by the scale on the top right hand side of Figure 4.1.2.

The next step involved turning the velocity field diagram into velocity profile diagram. Velocity profile is a diagram which shows the velocity of particles along a single plane. For the sake of consistency, the plane in which the velocity diagram will be drawn is set at angle between 210° to 225°. Figure 4.1.2.2 and Figure 4.1.2.3 summarize the process of getting velocity profile diagram.

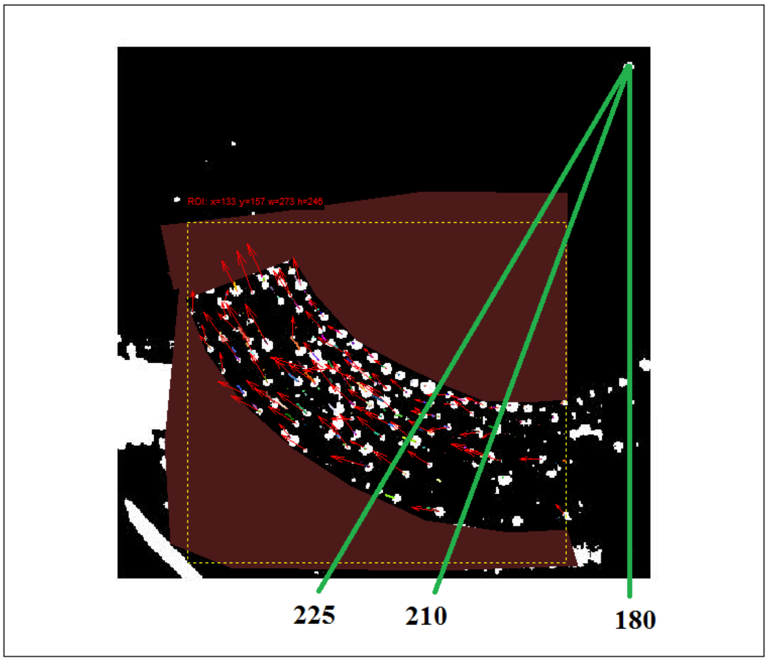


Figure 4.1.2.2 Section of the bed in which the velocity profile diagram is drawn (between 210° and 225°).

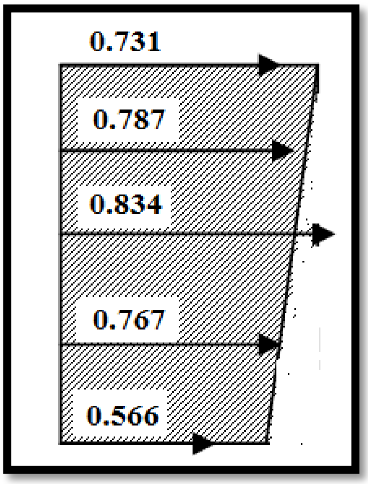


Figure 4.1.2.3 Velocity profile extracted from the analysed image showing five velocity arrows.

It should be noted that the original plane have more than five velocity arrows and most of them are not parallel to each other. However for the ease of analysis, only five arrows were chosen with near equidistant to one another and there are assumed to be parallel when the velocity profile is drawn.

For the example shown in Figure 4.1.2.3, the average velocity of particle of the section is the average of the five arrows which in this case is 0.737 m/s. This method is then being repeated for all of the images in the other 23 combinations of experimental parameters. The results are then tabulated which is available in Appendix C.

4.2.1 Discussion Overview

As stated earlier, the experiment carried out wield yield out a total of 24 sets of data. These are due to the combination of four blade angles, two blade inclination angles, and three particles' densities. To recall the objective of the experiment (as stated at Section 1.3) which is to investigate the effect of particle density, blade angle and blade inclination onto the velocity of particles inside the SFB. As such, only a partial of the data will be chosen in order to reflect the objective of the experiment.

4.2.2 Blade Angle Effect

To effectively show the effect of varying the blade angle, the other two parameters are kept constant which are blade inclination of 10° and particle C (density 1312 mg/cm^3). Figure 4.2.2 showed the comparisons.

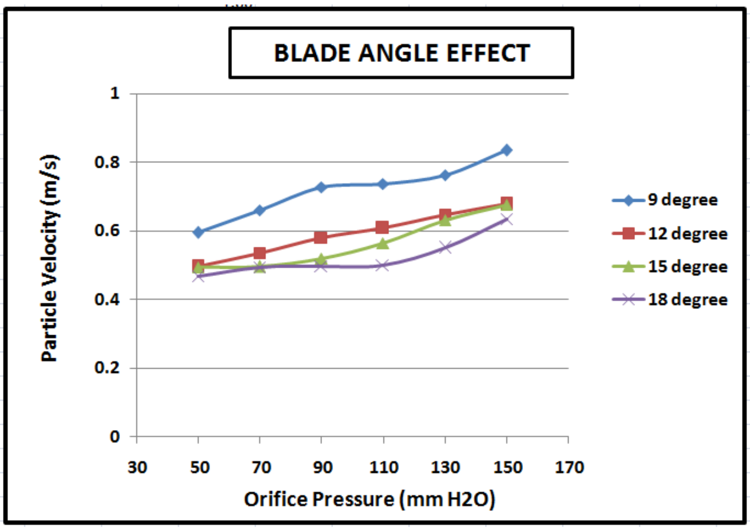


Figure 4.2.2 Variation of particle velocity for different blade angle.

In general, smaller blade angle will results in higher velocity of particle movement. As shown in Table 3.2, blade angle refers to the angle in between two sides of the blade. A smaller blade angle indicates smaller surface area of contact between the particles and the blades. As such, the friction force needed to be overcome for the larger blade is larger. Therefore it can be said that the minimum fluidization velocity is higher as the blade angle increases. This in turns means that the resultant particle velocity decreases as the blade angle gets larger.

Although Figure 4.2.2 does not exhibit a consistent proportion of velocity produced from one blade angle to another, however it can be said that approximately 6% velocity reduction occurred for every three degree increment in blade angle. This is determined based on straight line approximation applied to each curve. A further look into the graph revealed that the blade angle of 12°, 15° and 18° have similar particle velocity at certain orifice pressure. They are also more clumped together which may suggest that blade angle factor became less prominent as it get larger.

4.2.3 Blade Inclination Effect

For effectively showing the effect of blade inclination angle, the other two parameters are set constant which are blade angle of 9° and particle C (density 1312 mg/cm^3).

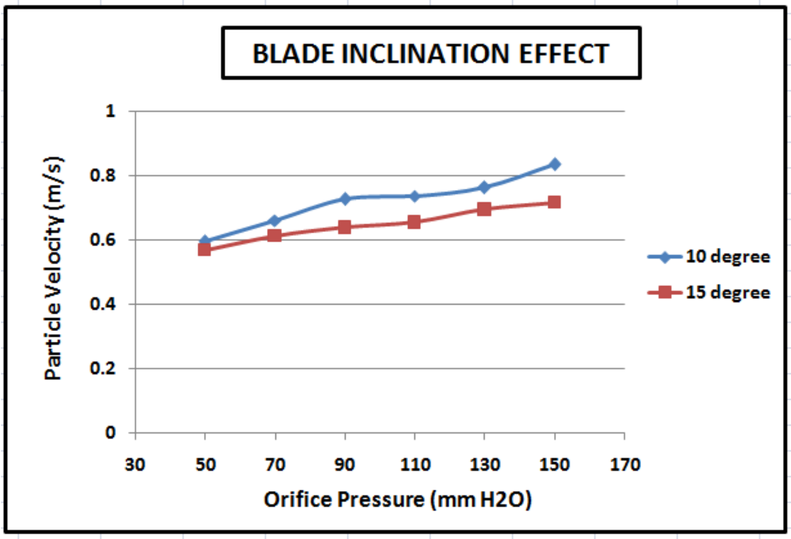


Figure 4.2.3 Variation of particle velocity for different blade inclination angle.

It is shown that smaller degree of blade inclination results in higher velocity of particles' movement. Referring to Figure 1.1.2.3, the air jet velocity will be distributed into two components after it passed through the blades which are the vertical component or VsinΘ, and another one is horizontal component or VcosΘ. The vertical component is responsible for fluidization motion whilst the horizontal component is responsible for swirling motion. Since particle velocity is dependent upon the swirling motion or the horizontal component of the velocity, the VcosΘ value decreases with increasing Θ value. This is determined to be the main reason for the result pattern shown by Figure 4.2.3.

A straight line approximation suggests that approximately 9% velocity reduction occurred for five degree inclination angle increment. It should be noted that due to the small particle size (6 mm of diameter), there is a limit to how much the blade inclination can be increased before the opening between the blades gets too large which will caused the particle to get sink in into the blades. Hence, only a certain limit of blade angle can be said will exhibit these results before it becomes null and void.

4.2.4 Particle Density Effect

As with the previous analysis, in order to analyse the effect of particle density, the other two parameters are kept constant which are blade angle of 9° and blade inclination angle of 10°.

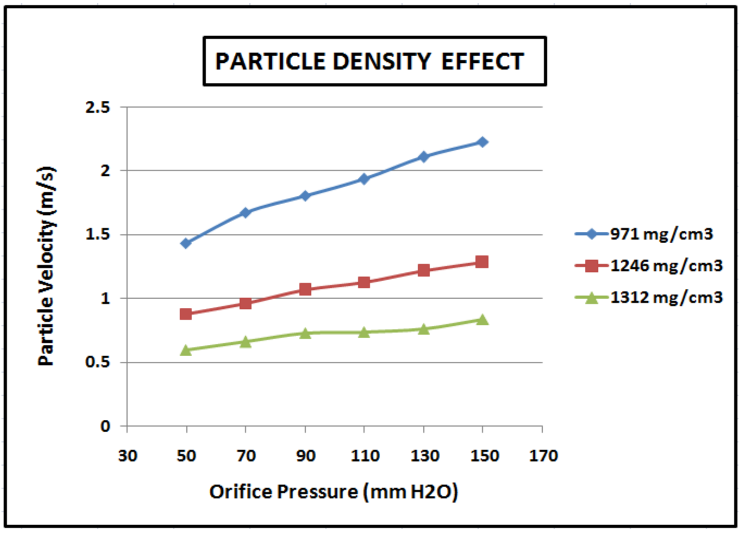


Figure 4.2.4 Variation of particle velocity for different particle density.

Seen from Figure 4.2.4, the less the density of the particle, the higher the velocity in which it swirls around inside the bed. One of the main factors influencing the velocity in which a particle moves is the mass of the particle itself. Although the whole bed among the three sets of particles is the same (1200 grams), each of the individual particles is not.

Particles of higher density will be heavier as each particle is having the same size (sphere of 6 mm diameter). Because of this, the air drag force needed to overcome the resultant weight will be higher for the particle of higher mass. Thus, this causes the heavier particle, i.e. the denser particle to swirl around slower given the same air jet velocity. Also based on straight line approximation of each curves in Figure 4.2.4, it can be said that for each 10% increment in particle density, its resultant velocity is decreased by 20% given the same experimental condition.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Through the experimented conducted, particle motion and the effects of varying air superficial velocity, blade angle, blade inclination angle and particle density is done using the PTV method. Particle velocity obtained from the analysis is tabulated and relevant graph is made based on the aim of the experiment. From the data collected, the following conclusions are made:

- Particle velocity increases roughly linearly with the orifice pressure drop.
- Approximately 6% particle velocity reduction for every 3° blade angle increment. However, as the blade angle gets larger, the differences in particle velocity become less distinct.
- Approximately 9% particle velocity reduction for every 5° blade inclination angle increment. It should be noted that there is a limit to how much the blade inclination angle can be increased before it become unusable as smaller particles will get stuck in between the blades.
- For every 10% increase in particle density, approximately 20% particle velocity reduction is observed. This is for the particle of class D of Geldart's classification.

The findings listed above will serve to develop a more enhanced version of SFB unit which up until now are limited in terms of industrial application due to the lack of understanding in terms of particle dynamics characteristics. These results may also serve as the validation guidelines for future work or studies into the particle flow characteristics within the SFB. It may also serve as a reference in calculating the heat transfer coefficient which can be obtained by calculating slip velocity from the data obtained. The findings also can serve as a guidelines for certain industries on what types of SFB design and particle density should be chosen if they want to achieve certain velocity requirements.

The experimental findings presented here can be further enhanced in the future work. One area that can be explored is to determine the heat transfer coefficient based on the particle velocity. The correlation between the heat transfer coefficient and particle velocity can be determined based on the slip velocity. Another area in which the particle dynamics can be further studied is the velocity of particles at the middle of the bed, particularly the region that involved in the bubbling and slugging process. These processes are essential in determining the quality of the whole fluidization process and studies into this aspect is highly recommended.

Conclusively, SFB has a very high potential to be utilised fully in today's industrial application. Its improvement upon the conventional fluidized bed has overcome many drawbacks such as reduction in elutriation, particle limitation and also bed pressured drop. However, in order to fully utilize its potential, more studies should be done in order to further improve its performance and hence make it more marketable for the use in various industries.

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APPENDIX A

EXPERIMENT SETUP

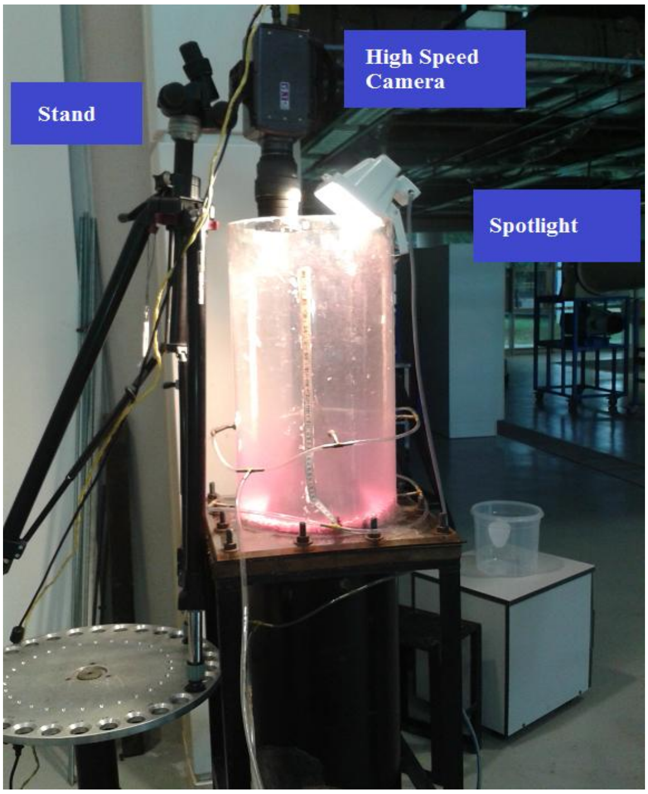

Figure A-1 Major apparatus setup

Figure A-2 Blade arrangement setup.

APPENDIX B

USING MATLAB SOFTWARE TO PERFORM PTV ANALYSIS

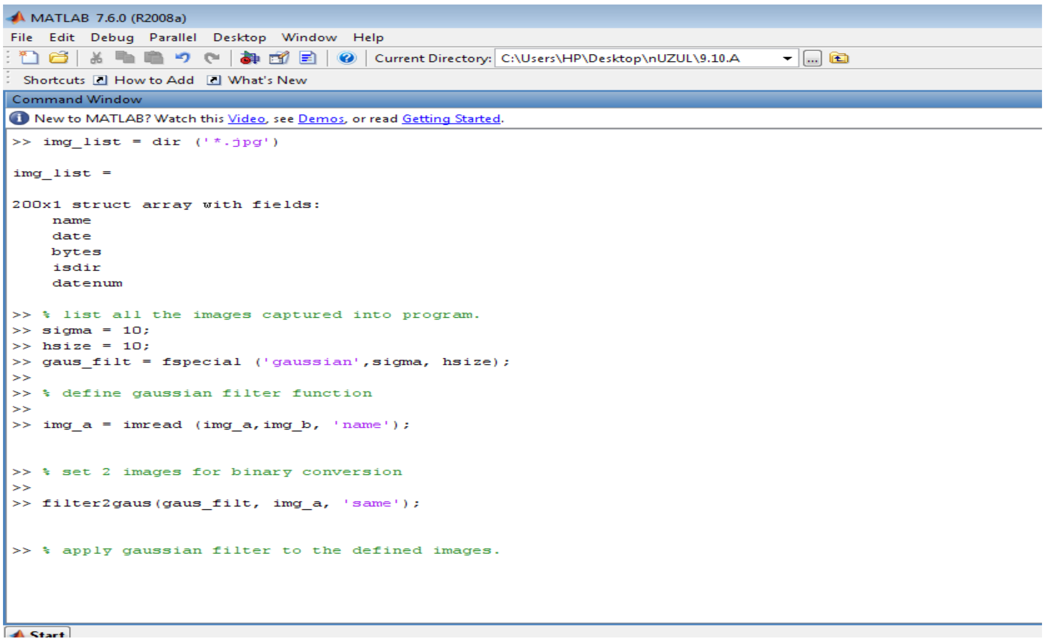

Figure B-1 MATLAB coding to apply Gaussian filter to convert grayscale image into binary form.

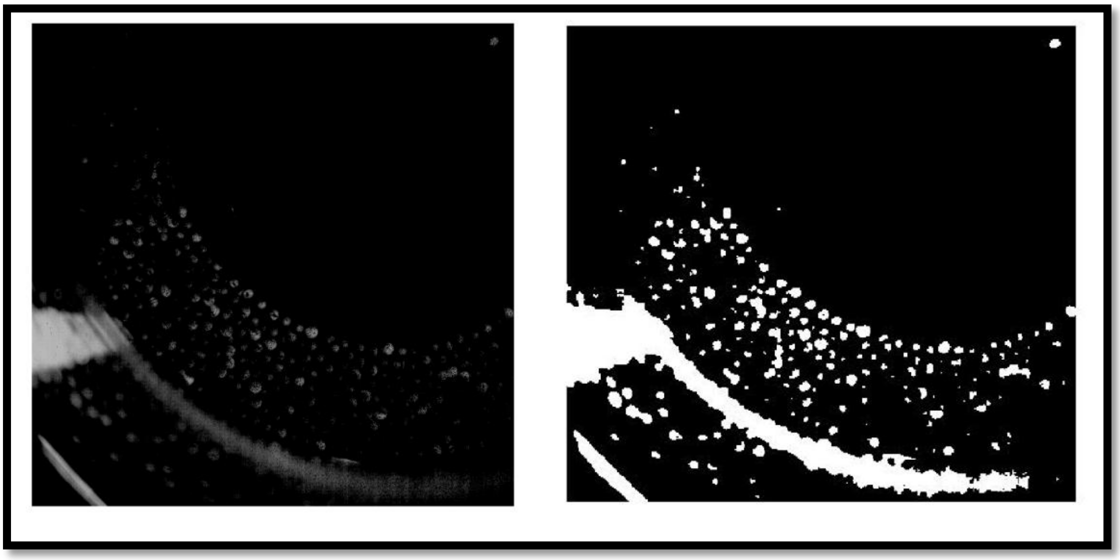

Figure B-2 From left; original grayscale image, binary image converted by using Gaussian filter.

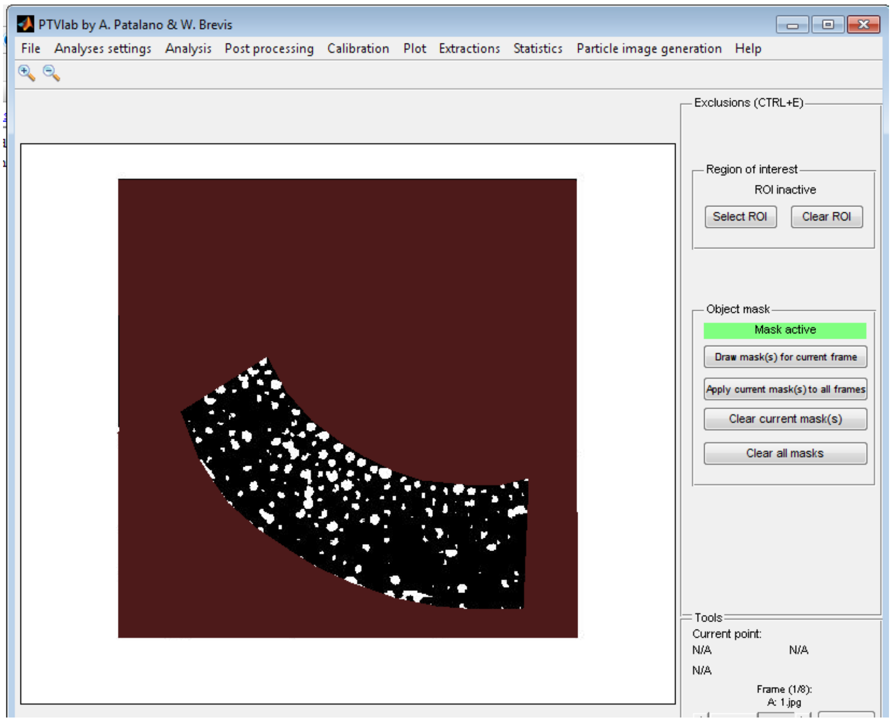

Figure B-3 Masking out unwanted area.

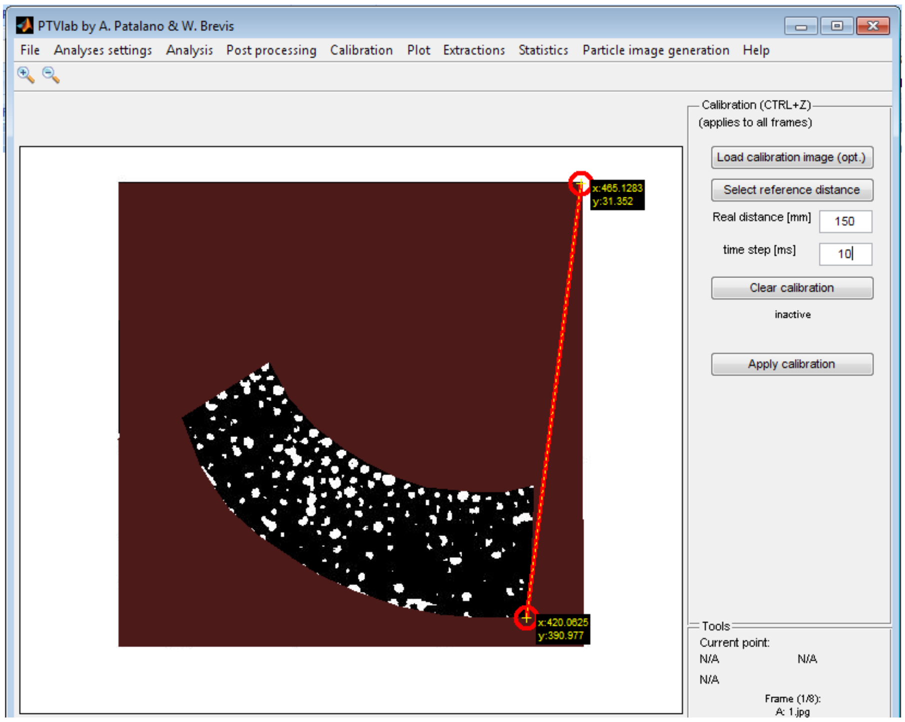

Figure B-4 Defining calibration distance.

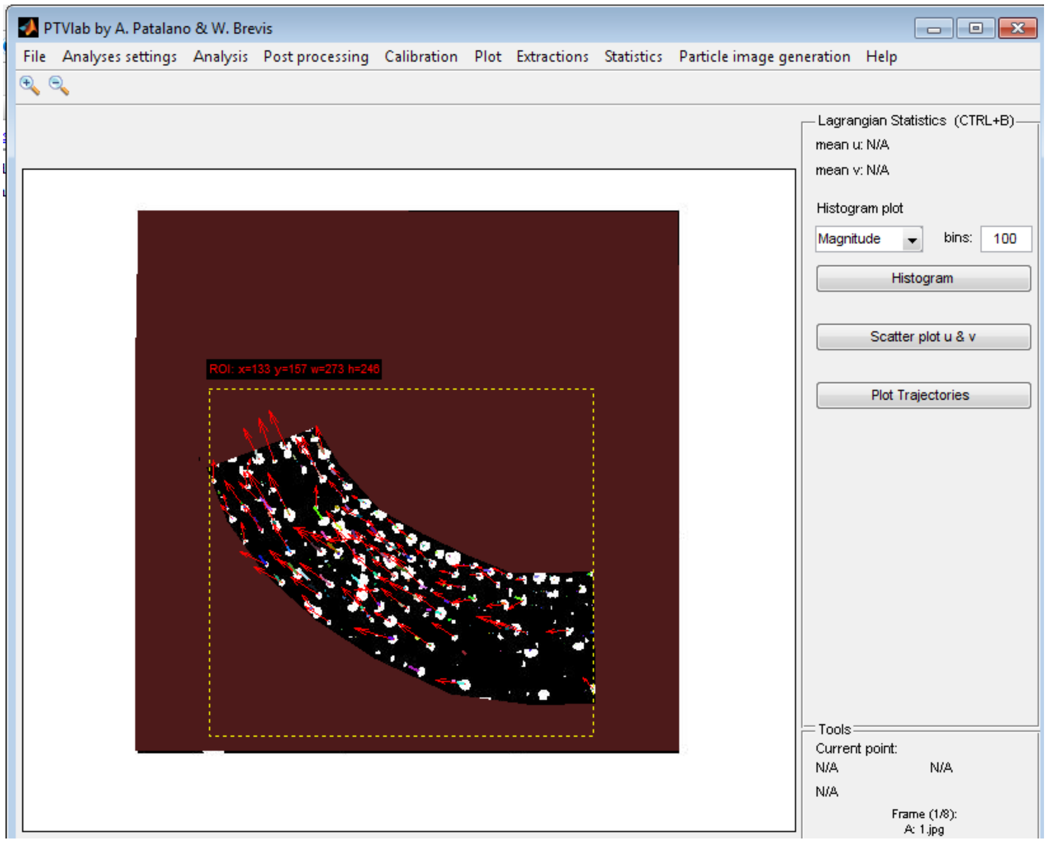

Figure B-5 Velocity field generated.

APPENDIX C

RAW PARTICLE VELOCITY DATA

COMBINATION 1: BLADE ANGLE 9°, INCLINATION 10°

PARTICLE A

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	1.433
70	1.672
90	1.803
110	1.933
130	2.107
150	2.226

PARTICLE B

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.876
70	0.963
90	1.064
110	1.125
130	1.213
150	1.28

PARTICLE C

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.594
70	0.66
90	0.727
110	0.737
130	0.763
150	0.834

COMBINATION 2: BLADE ANGLE 9°, INCLINATION 15°

PARTICLE A

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	1.373
70	1.54
90	1.592
110	1.715
130	1.909
150	1.923

PARTICLE B

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.839
70	0.904
90	0.924
110	0.964
130	1.024
150	1.039

PARTICLE C

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.569
70	0.613
90	0.638
110	0.654
130	0.695
150	0.717

COMBINATION 3: BLADE ANGLE 12°, INCLINATION 10°

PARTICLE A

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	1.194
70	1.37
90	1.411
110	1.464
130	1.645
150	1.652

PARTICLE B

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.73
70	0.789
90	0.839
110	0.895
130	0.953
150	0.981

PARTICLE C

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.495
70	0.534
90	0.58
110	0.607
130	0.646
150	0.677

COMBINATION 4: BLADE ANGLE 12°, INCLINATION 15°

PARTICLE A

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	1.144
70	1.325
90	1.361
110	1.414
130	1.61
150	1.622

PARTICLE B

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.67
70	0.759
90	0.808
110	0.845
130	0.943
150	0.947

PARTICLE C

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.519
70	0.573
90	0.588
110	0.614
130	0.65
150	0.678

COMBINATION 5: BLADE ANGLE 15°, INCLINATION 10°

PARTICLE A

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	1.233
70	1.4
90	1.371
110	1.405
130	1.636
150	1.676

PARTICLE B

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.754
70	0.806
90	0.815
110	0.859
130	1
150	1.025

PARTICLE C

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.494
70	0.495
90	0.518
110	0.563
130	0.63
150	0.675

COMBINATION 6: BLADE ANGLE 15°, INCLINATION 15°

PARTICLE A

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	1.146
70	1.305
90	1.276
110	1.382
130	1.51
150	1.567

PARTICLE B

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.724
70	0.773
90	0.789
110	0.859
130	0.973
150	0.998

PARTICLE C

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.464
70	0.475
90	0.488
110	0.533
130	0.601
150	0.646

COMBINATION 7: BLADE ANGLE 18°, INCLINATION 10°

PARTICLE A

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	1.204
70	1.376
90	1.381
110	1.405
130	1.506
150	1.635

PARTICLE B

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.724
70	0.779
90	0.785
110	0.834
130	0.876
150	0.901

PARTICLE C

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.468
70	0.493
90	0.496
110	0.499
130	0.549
150	0.634

COMBINATION 8: BLADE ANGLE 18°, INCLINATION 15°

PARTICLE A

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	1.104
70	1.258
90	1.297
110	1.387
130	1.441
150	1.475

PARTICLE B

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.694
70	0.756
90	0.775
110	0.799
130	0.846
150	0.879

PARTICLE C

Orifice Pressure (mm H2O)	Particle Velocity (m/s)
50	0.433
70	0.463
90	0.475
110	0.489
130	0.512
150	0.6